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Plant Water Stress at Various Growth Stages and Growth and Yield of Soybeans

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ABSTRACT

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In the Southern High Plains of the U.S.A., where water for irrigation is being depleted, drought-tolerant crops are extensively grown under limited irrigation where less water is applied than is required for potential evapotranspiration and maximum yield. This study was conducted (1) to determine the effects of plant water stress at various growth stages on growth and yield of soybeans [*Glycine max* (L.) Merr.] and (2) to assess the adaptability of the soybean plant to limited irrigation in the stressful climate of the Southern High Plains. The 3-year study was conducted on Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll). Soybeans ('Douglas', indeterminate, maturity group IV) were grown with different irrigation treatments designed to subject the plants to water deficits at different growth stages. Stress intitiated during R1 (early flowering) or R2 (full bloom) and extending to R3 (beginning pod development) reduced seed yields by 9-13%. But, when stress was extended to R4.5, yields were reduced by 46%. Stress beginning at R3 and extending to R4.5 reduced yields by 19%. Stress imposed at R5 and relieved at R6 reduced yields 15% in one year and 46% in a more stressful year. Stress imposed at R5 and extending to the end of the growing period (5 weeks) reduced yields by 45% in the less-stressful year and by 88% in the other. Stress throughout the last 3 weeks of the growing period (beginning at R6) reduced yields by 21 and 65%, respectively, in the two years. Water-use efficiency was not increased under limited irrigation. Soybeans are amenable to limited irrigation under the stressful climate of the Southern High Plains, but their vulnerability to drought stress during seed development complicates management. They are more suited for limited irrigation than is corn (*Zea mays* L.) but are less suited than are grain sorghum [*Sorghum bicolor* (L.) Moench], cotton (*Gossypium hirsutum* L.) or wheat (*Triticum aestivum* L.).

INTRODUCTION

Irrigated soybeans [*Glycine max* (L.) Merr.] have been grown on the Southern High Plains for many years. The area devoted to soybeans has been quite

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variable since they are used as a 'catch' crop when cotton (*Gossypium hirsutum* L.) stands are lost due to surface crusting, seedling diseases, or hail. For instance, the area of soybeans on the Texas High Plains varied from 28 000 ha in 1981 to 186 000 in 1982. The average annual area is about 30 000 ha. Possibly because of the limited area, the water requirements and effects of plant water stress on soybean growth and production have not been studied extensively under the stressful conditions in this semiarid area.

Groundwater depletion from the Ogallala Aquifer, and increasing energy costs for pumping, emphasize the need for conservation and efficient use of water. Grain sorghum [*Sorghum bicolor* (L.) Moench], wheat (*Triticum aestivum* L.), and cotton are extensively grown under limited irrigation where less water is applied than is required for potential evapotranspiration (ET) and maximum yield (Musick and Dusek, 1980). With limited irrigation, most existing irrigation systems can still be used. With drought-tolerant crops and significant seasonal rainfall, water-use efficiency can be increased with limited irrigation (Schneider et al., 1969; Stewart et al., 1983). Corn (*Zea mays* L.) is not adapted for limited irrigation in this area (Musick and Dusek, 1980), whereas soybeans may possibly be so adapted because photosynthesis continues at lower leaf-water potentials than it does in corn (Boyer, 1970).

Soybean seed yield is least sensitive to water deficits during the vegetative stage, more sensitive during flowering and pod set, and most sensitive during pod fill (Shaw and Laing, 1966; Shipley and Regier, 1970; Dusek et al., 1971; Doss et al., 1974; Sionit and Kramer, 1977; Constable and Hearn, 1980; Korte et al., 1983a,b). Constable and Hearn (1980) found that irrigating frequently before pod filling was unnecessary since moderate irrigation frequency in the vegetative stage was sufficient to grow a plant of satisfactory size to set enough seeds for maximum yield. Laing studied the effects of stress during eight periods from beginning flowering through bean fill (D.R. Laing, 1965, unpublished Ph.D. thesis, Iowa State University; reported by Shaw and Laing, 1966). Stress was applied only during one period, the plants being adequately watered the rest of the season. The maximum reduction in yield occurred when plants were stressed during the last week of pod development and during bean filling. There was less yield reduction from stress during late flowering–early pod development, and stress during early flowering or the final stage of bean filling did not reduce yields below those of the unstressed controls. Studies by the other authors mentioned, though less specific for determining most sensitive periods, substantiate findings reported by Shaw and Laing.

Laing (Shaw and Laing, 1966) also studied the effects of stress on pod numbers, mature beans per pod, and bean size. Maximum reduction in pod number occurred from stress during late flowering through pod development (R2–R5), with less reduction during bean filling. Stress applied during early flowering or during the final stages of bean filling did not affect pod numbers. It was stated that the effect of stress on pod number was apparently due to flower abortion during the main flowering period and pod abortion during the period of rapid pod growth after flowering. The number of mature beans per pod was decreased by stress during bean filling, with the difference from control being due to immature (unfilled embryo) beans. The greatest reduction in bean size occurred when stress was imposed during bean filling.

In a growth chamber study, Sionit and Kramer (1977) found that plants stressed during flower induction and flowering (R1–R2) produced fewer flowers, pods, and seeds than did controls. Stress during early pod formation (R3) caused the greatest reduction in number of pods and seeds at harvest. Seed yield was reduced most by stress during early pod formation (R3) and pod filling. Their results agree with those reported by Shaw and Laing (1966) except in that a more severe yield reduction was experienced from stress during R3.

Dusek et al. (1971) found that soybean yields were maintained by irrigating when soil moisture in the 0–0.6 m depth was depleted to 40% available, but were substantially reduced when it was depleted to 20% available. Initially, Constable and Hearn (1980) thought that yields could be maintained when soil moisture was depleted to 40% available in their environment (New South Wales) but, in a drier season, found that available soil moisture should be maintained above 60% during pod fill. They concluded that available soil water could be depleted below 60% during the vegetative stage, saving one or two of the irrigations then applied in commercial practice. Thompson (1977) found that for maximum yields of 'Clark 63' soybeans, it was necessary to keep water available until physiological maturity.

Shipley and Regier (1968, 1970) conducted a series of irrigation studies on soybeans in the Southern High Plains, but their treatments involved irrigation at designated growth stages without regard to soil water deficits or plant water stress. The field studies reported by Shaw and Laing (1966) were conducted under the climatic conditions of the Corn Belt. To adequately assess the effects of water deficits in the stressful climate of the Southern High Plains, it was necessary to conduct field studies in that area. The objectives of this study were (1) to determine the effects of plant water stress at various growth stages and yield of soybeans and (2) to assess the adaptability of the soybean plant to limited irrigation in the stressful climate of the Southern High Plains.

METHODS AND MATERIALS

The 3-year study was conducted on Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) at the USDA Conservation and Production Research Laboratory, Bushland, Texas. Soybeans ('Douglas', indeterminate, maturity group IV) were grown under different irrigation treatments designed to subject the plants to water deficits at different growth stages. Eight treatments were planned for each year; however, rainfall eliminated the need for some of the planned irrigation in two of the three years. In 1981, precipitation furnished adequate water from rapid pod development (growth stage R4; Fehr et al., 1971) to maturity; thus, only four irrigation treatments were needed. Eight treatments were completed in both 1982 and 1983; however, they differed between years as a result of differing precipitation patterns. Each treatment was replicated twice in a randomized block design. Irrigation treatments and dates, amounts of water applied, and seasonal water use are given in Table 1. Irrigations were spaced so that plants were approaching stress when water was applied. Thus, stress began the day following irrigation of the unstressed treatments. The approach of stress was determined by visual observation. As soybean plants become stressed, leaf orientation changes and their appearance is different from that of well-watered plants. Dates of stress periods and stages of plant growth during stress are given in Table 2.

The site was a series of 9×43-m level-bordered plots. In 1981 and 1982, studies were conducted on plots that had been fallowed during the previous year. In 1983, they were conducted on the same plots as in 1982. In early spring, plots were bedded and trifluralin [2,6-dinitro N,N-dipropyl-4 (trifluoromethyl) benzenamine] was applied for weed control. Inoculated seeds were bed-planted in 0.76-m rows at rates of about 40 seeds per m^2. Planting dates were 11 May 1981, 23 April 1982, and 11 May 1983. In 1981 and 1983, planting was in dry soil and about 50 mm of irrigation was applied the following day. In 1982, plots were irrigated after bedding and before planting.

In 1981, the plant population averaged 16 per m^2; this was thin, due to poor germination and emergence. In 1982, the final stand averaged about 17 plants per m^2 after being reduced by hail soon after emergence. In 1983, we obtained a uniform stand of 43 plants per m^2. In 1981 and 1982, irrigation treatments were initiated in mid July (growth stage R2) when plant water stress was first encountered. In 1983, with the greater stand density and lower precipitation during May and June, stress was encountered in late June and treatments were initated on 29 June (growth stage R1).

Irrigation water was applied to level-border plots through gated pipe and measured with a propeller-type meter. In 1981 and 1982, each application was 100 mm. In 1983, application amounts were reduced to 80 mm to increase the range of water deficits. Soil water content, determined by the neutron scatter method at one location per plot to a depth of 1.8 m in 20-cm increments, was measured before each irrigation and when the crop reached maturity. Water use was determined from a water balance using soil water data and measured rainfall and irrigation applied to the level-border plots. Drainage of water below 1.5-m depth on this slowly permeable clay loam is considered negligible (Aronovici and Schneider, 1972). No runoff occurred from the bordered plots.

Plants were sampled at intervals throughout each season to determine plant

TABLE 1

Treatments and irrigation dates, seasonal irrigation water applied, and seasonal water use

Treatment (stage stressed)		Growth stage[†]								
		R1	R2	R3	R5	R5.5	R6	R6.5	Seasonal irrigation amount (mm)	Seasonal water use (mm)
	Emergence	Beginning bloom	Full bloom	Beginning pod development	Beginning seed development	Mid-seed development	Full seed development	Bottom leaves yellowing		
1981	5/12		7/15	7/29						
UN[‡]	x		x	x					250	719
R2-3	x			x					150	597
R3-4.5	x		x						150	652
R2-4.5									50	545
1982			7/19		8/12	8/19	8/26	9/9		
UN			x		x		x	x	410	813
R2-3					x		x		200	668
R2-3/5-7									—	481
R5-5.5/6.5-7			x			x			200	635
R5-6			x				x		200	675
R5-7			x						100	598
R6-7			x		x				200	720
R6.8-7			x		x		x		300	730
1983	5/12	6/29	7/13	7/27	8/10		8/24	9/7		
UN	x	x	x	x	x		x	x	530	685
R1-2	x		x	x	x		x	x	450	620
R1-3	x			x	x		x	x	370	534
R2-3	x	x		x	x		x	x	450	598
R5-6	x	x	x	x			x	x	450	586
R5-7	x	x	x	x					290	467
R6-7	x	x	x	x	x				370	571
R6.5-7	x	x	x	x	x		x		450	635

[†]R stages indicate reproductive stages according to Fehr et al., 1971.
[‡]Unstressed.

TABLE 2

Effects of plant water stress treatments on soybean seed yield, seed weight, seed numbers, plant height, and water use efficiency, 1981-1983

Treatment (stage stressed)	Calendar dates stressed	Water use deficit[1] (mm)	Water use deficit[1] (%)	Yield (Mg/ha)	Avg. seed weight (mg/seed)	Seed density seeds/m²	Plant height (m)	Seasonal W.U.E. (kg/m³)
1981								
UN	Unstressed	—	—	4.16	187	1936	0.68	0.58
R2-3	7/15-7/29	84	62	3.66	223	1433	0.56	0.61
R3-4.5	7/29-8/ 7	39	58	3.38	225	1305	0.63	0.54
R2-4.5	7/15-8/ 7	135	66	2.24	242	866	0.51	0.41
LSD (0.05)				0.49	16	148	0.06	0.07
1982								
UN	Unstressed	—	—	4.26	202	1857	0.82	0.52
R2-3	7/19-7/31	—[2]	—	4.06	209	1698	0.64	0.61
R2-3/5-7	7/19-7/31, 8/12-mat.	—[2]	—	2.00	137	1293	0.63	0.42
R5-5.5/6.5-7	8/12-8/19, 9/ 2-mat.	—[2]	—	4.33	164	2313	0.78	0.68
R5-6	8/12-8/26	45	37	3.60	175	1806	0.83	0.53
R5-7	8/12-mat.	198	57	2.34	121	1686	0.82	0.39
R6-7	8/26-mat.	94	42	3.35	153	1957	0.78	0.47
R6.8-7	9/ 9-mat.	84	86	4.86	186	2270	0.82	0.67
LSD (0.05)				0.68	35	446	0.07	0.12
1983								
UN	Unstressed	—	—	3.13	167	1634	0.90	0.46
R1-2	6/29-7/13	—[2]	—	2.69	159	1475	0.80	0.43
R1-3	6/29-7/27	74	75	2.74	187	1277	0.65	0.51
R2-3	7/13-7/27	64	56	2.86	187	1333	0.77	0.48
R5-6	8/10-8/24	49	45	1.69	148	995	0.85	0.29
R5-7	8/10-mat.	218	77	0.37	68	503	0.88	0.08
R6-7	8/24-mat.	114	65	1.10	91	1041	0.86	0.19
R6.5-7	9/ 7-mat.	50	68	2.90	147	1723	0.90	0.46
LSD (0.05)				0.25	10	179	0.06	0.05

[1]Water use on unstressed treatment less that on stressed treatment.

$$\% = 1 - \frac{\text{use on stressed tmt}}{\text{use on unstressed tmt}} \times 100.$$

[2]Missing data.

[3]Water use efficiency: kg seed produced produced per m³ water used.

stand, plant height, green leaf area, and wet and dry weights of plants. Two subsamples (adjacent 1-m row lengths) were taken from each plot. The moving cubic spline technique was used to draw leaf area index (LAI) curves as a function of time.

Yield measurements were made by harvesting two adjacent rows, 4.6 m long, at two sites per plot. Seed moisture content was determined and yields reported on a 13% moisture basis. Seed weights were determined (on 500 seed samples) and are reported on a dry-weight basis. One hundred pods were collected at random from each plot, and beans in these pods were counted.

Leaf water potential determinations were made on 0.24-cm^2 leaf samples with leaf cutter thermocouple psychrometers on upper sunlit leaves shortly after solar noon on selected days. Water potentials were determined after equilibration in a constant-temperature water bath for 3 h.

Analyses of variance were calculated on the yield, yield component, plant height, and water use efficiency (WUE) data. Means were compared using LSD values ($P = 0.05$).

RESULTS AND DISCUSSION

Daily maximum and minimum temperatures and precipitation for the three growing seasons are presented in Fig. 1, and a summary of climatic conditions is given in Table 3. In 1981, maximum temperatures were below the long-term averages in May but near average for the remainder of the growing season. In 1982, maximum temperatures were below average until mid-August but were slightly above average thereafter. In 1983, maximum temperatures were below the long-term average during May and June, near average in July, and above average in August and September. Seasonal precipitation was 166% of average in 1981, 120% of average in 1982, and 50% of average in 1983. Wind movement during the three seasons was similar and near the long-term average.

Dates of stress periods, plant stages at which stress periods occurred, and water use deficits during stress periods are given in Table 2. Water use deficits are defined as the percent to which water use on the stressed treatment was less than that on the unstressed treatment. We assumed 100% irrigation efficiency in calculating water use.

Numbers of seeds per pod were not significantly affected by treatments; thus, numbers of seeds per unit area (Table 2) reflect the effect of treatments on flower or pod abortion. Average numbers of seeds per pod were 2.7, 2.5, and 2.7 in 1981, 1982, and 1983, respectively.

Effects of stress during early and mid-reproductive stages

In general, early-season stress (beginning in R1, R2, or R3) reduced LAI (Figs. 2, 3, and 4), plant height, seed numbers, and yield (Table 2). These stress treatments resulted in reduced seed number but the plants compensated for this by increased seed weight. The earliest that plants were stressed was at stage R1 (beginning flowering).

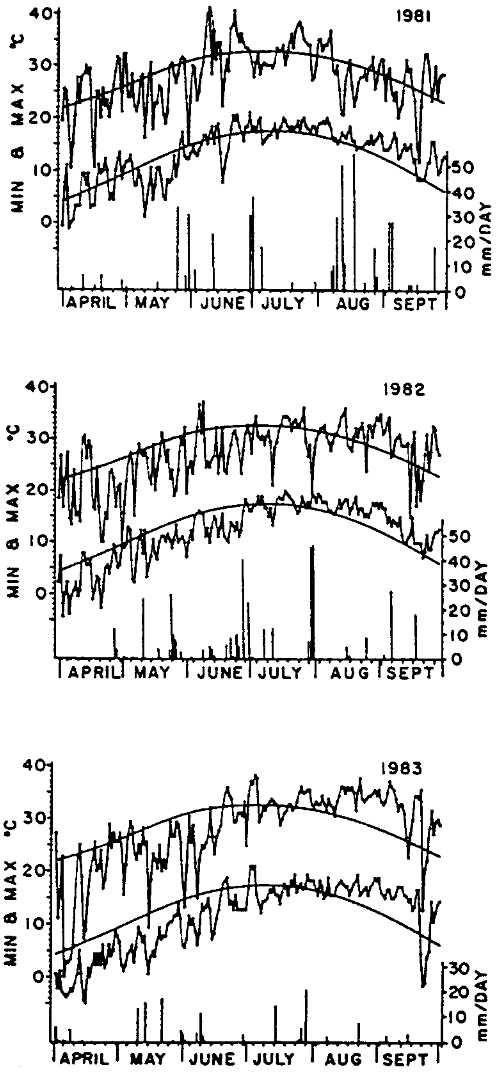


Fig. 1. Daily maximum and minimum air temperatures and precipitation, 1981–1983. Air temperatures are compared with long-term average.

In 1983, plants in stress treatment R1–2 were stressed for 2 weeks and plants in stress treatment R1–3 were stressed for 4 weeks. During the stress periods, leaf water potentials of stressed plants were lower than those of unstressed plants (Table 4). Leaf area indexes were sharply reduced (Fig. 4). The unstressed plants reached a maximum LAI near 6.5, whereas maximums for stress treatments R1–2 and R1–3 were near 5.5 and 3.5, respectively. Plant heights for stress treatments R1–2 and R1–3 were reduced by 11 and 27%,

TABLE 3

Summary of May-September climatic data for 1981-1983 at the USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX

	May	June	July	Aug.	Sept.	Total or Avg.
1981						
Precipitation (mm)	62	105	25	237	113	542
Evaporation[1] (mm)	207	245	218	159	113	942
Temperature — Max. (°C)	25.1	32.3	32.3	29.0	25.8	28.9
— Min. (°C)	9.3	16.1	18.0	16.5	12.7	14.5
Solar radiation[2] (MJ m^2 day^{-1})	23.9	27.3	25.2	21.8	18.3	23.3
Wind movement (m sec^{-1})	4.8	4.5	3.9	3.2	2.6	3.8
1982						
Precipitation (mm)	44	104	167	20	55	390
Evaporation (mm)	140	156	168	156	157	777
Temperature — Max. (°C)	24.4	27.9	30.9	31.1	28.3	28.5
— Min. (°C)	9.2	13.1	17.3	17.1	12.3	13.8
Solar radiation (MJ m^2 day^{-1})	23.4	—	—	—	18.2	—
Wind movement (m sec^{-1})	4.1	4.1	3.7	2.9	3.5	3.7
1983						
Precipitation (mm)	72	32	44	8	8	164
Evaporation (mm)	164	164	247	224	221	1020
Temperature — Max. (°C)	23.7	27.7	33.3	34.2	30.3	29.8
— Min. (°C)	6.7	12.4	16.9	17.1	12.9	13.2
Solar radiation (MJ m^2 day^{-1})	23.4	24.5	26.4	23.5	19.7	23.5
Wind movement (m sec^{-1})	4.3	4.0	4.3	2.7	4.4	3.9
44-year average[3]						
Precipitation (mm)	69	75	66	71	45	326
Evaporation (mm)	201	230	247	222	180	1080
Temperture — Max. (°C)	26.2	31.1	32.6	31.7	28.2	30.0
— Min. (°C)	9.6	14.9	17.4	16.4	12.3	14.1
Wind movement (m sec^{-1})	4.5	4.3	3.8	3.6	3.8	4.0

[1]From 60 cm sunken Young's pan. (Seasonal avg. ratio to class A pan at Bushland=0.68).
[2]2-m height.
[3]Precipitation, temperature, and wind, 1939-1982, Evaporation, 1940-1983.

respectively (Table 2). Seed numbers were not significantly reduced by the shorter stress period (R1-2) but were reduced by the longer stress period (R1-3). The reduction in seed numbers (R1-2 compared to R1-3) was apparently compensated for by the increase in seed weight. Thus, yields were similar for the two treatments but less than for the unstressed treatment. The reduction in plant height was not an important factor in this study because the

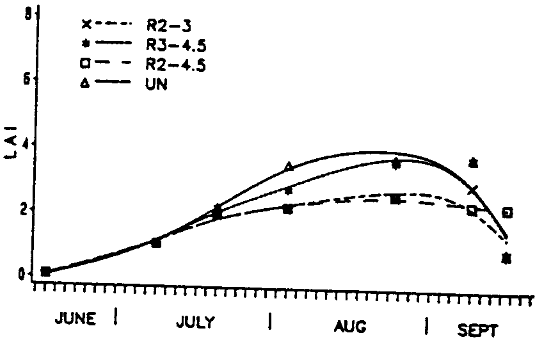


Fig. 2. Leaf area indexes as affected by stress, 1981.

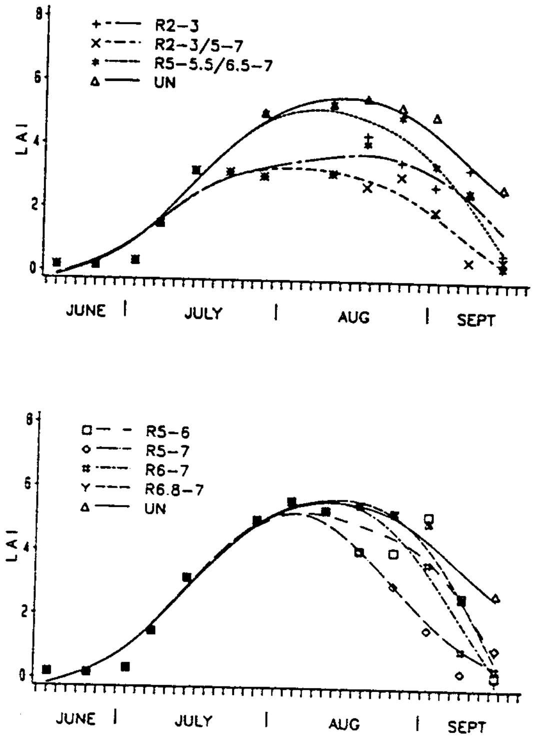
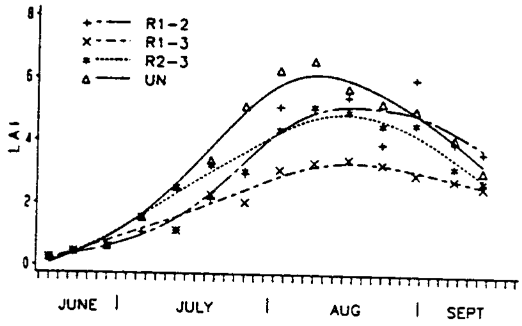


Fig. 3. Leaf area indexes as affected by stress, 1982. Upper: stress during flowering and pod set. Lower: stress during seed filling.

plants were hand-harvested. However, a greater proportion of pods near the soil surface increases susceptibility to machine-harvest losses.

Stress periods were initiated during R2 (full bloom) in all three seasons. The R2–3 treatments had 2-week stress periods beginning at this stage. Leaf area indexes and plant heights were reduced by the treatment in all years (Figures 2, 3, 4; Table 2). Seed numbers and yields were reduced and seed weights



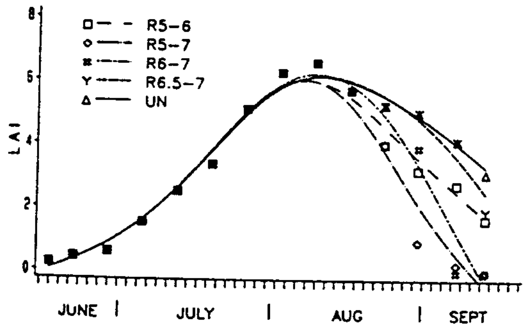


Fig. 4. Leaf area indexes as affected by stress, 1983. Upper: stress during flowering and pod set. Lower: stress during seed filling.

were increased in all years. However, these effects were statistically significant only in 1981 and 1983. The yield reduction was 12% in 1981 and 9% in 1983. In 1981, stress began at R2 and extended to R4.5 (3 weeks) before being terminated by rains (R2–4.5). Plant height was further reduced (compared to 2 weeks of stress). Compared to those for the unstressed treatment, yields were reduced by 46%, seed numbers by 58%, and weights of seeds that developed during a period when rainfall was adequate were increased by 29%. The increase in seed weight partially compensated for the reduction in seed numbers. As previously mentioned, the 2-week stress period (R2–3) reduced yields only 12%. The drastic reduction from the added week of stress resulted from arrested stem growth that stopped new blossoms and aborted some pods set at terminal nodes. With the reduction in pod numbers, translocation to seeds did not deplete leaf assimilates and leaves did not senesce and abscise as they normally do. Plants on all except this treatment had matured and lost most of their leaves by 15 September, but those on R2–4.5 remained green after the pods matured.

Stress beginning in stage R3 occurred in only one season (1981). Stress began at R3 and lasted for 9 days (R3–4.5). The effects of the treatment on

TABLE 4

Post solar-noon leaf water potentials (MPa) as affected by plant water stress, 1981-1983 (avg. 3 readings)

Date		Treatment (stage stressed)							
1981		UN[1]		R-3	R3-4.5	R2-4.5			
July	10	−1.38							
	13	−1.48							
	20	−1.50		−1.81					
	23	−1.58		−2.04					
	27	−1.77		−2.33					
Aug.	3	−1.34			−2.22	−240			
	20	−1.23				−1.44			
Sept.	3	−1.38				−1.63			
1982		UN		R2-3/5-7	R5-5.5/ 6.5-7	R5-6	R5-7	R6-7	R6.8-7
June	21	−1.43		Same as UN	Same as UN	Same as R5-5.5/ 6.5-7	Same as R5-6	Same as UN	Same as UN
	30	−1.29							
July	6	−1.12							
	13	−1.14							
	16	−1.41							
	19	−1.07		−1.35					
	22	−1.13		−1.76					
	26	−1.51		−1.63					
	29	−1.04		−1.70					
Aug.	5	−1.80		−1.94	−1.64				
	9	−1.57		−1.05	−1.51				
	12	−1.17			−1.59				
	19	−1.34		−1.88	−1.93				
	23	−1.80		−2.54		−2.43			
	26	−1.48		−2.22				−1.43	
	30	−1.50		−3.12				−2.00	
Sept.	3	−1.31		−2.68	−1.93	−1.68	−2.16	−1.95	
	9	−1.45		−1.87	−1.85	−1.83	−1.66	−1.93	
	13	−1.42		−2.43	−2.00	−2.03	−2.42	−1.97	−1.55
1983		UN	R1-2	R1-3	R2-3	R5-6	R5-7	R6-7	R6.5-7
June	23	−1.85	Same as UN	Same as UN	Same as UN	Same as UN	Same as R5-6	Same as UN	Same as UN
	27	−1.82							
	30	−1.85							
July	5	−1.51	−1.95						
	8	−1.28	−1.51						
	11	−1.68	−2.06						
	12	−1.93	−2.06						
	18	−1.58	−1.57	−1.79	−2.08				
	21	−1.57	−1.48	−2.13	−2.35				
	25	−2.10	−2.13	−2.05	−2.10				
	28	−1.87	−1.66	−1.87	−1.69	−1.72			

1983		UN	R1-2	R1-3	R2-3	R5-6	R5-7	R6-7	R6.5-7
Aug.	1	−1.59	−1.43	−1.71	−1.49	−1.41			
	2					−1.49			
	4	−1.48	−1.49	−1.55	−1.53	−1.41			
	8	−1.63	−1.84	−1.31	−1.62	−1.75			
	11	−1.57	−1.46	−1.36	−1.34	−2.06			
	15	−1.52	−1.55	−1.22	−1.62	−2.43			
	18	−1.75	−1.79	−1.71	−1.94	−3.39			
	22	−2.02	−2.13	−2.03	−2.26	−3.17			
	25	−2.10	−1.81	−1.88	−2.17	−2.28	−2.82	−2.42	
	29	−1.98	−1.95	−1.64	−1.83	−2.11	−3.32	−2.94	
Sept.	1	−2.20	−2.08	−1.48	−2.14	−2.19	−3.49	−3.06	
	7	−2.34	−2.00	−1.85	−2.05	−2.07			
	12	−1.62		−1.33					−3.06
	15	−1.69		−1.49					−2.96
	19	−2.24		−2.14					−2.88

[1]UN = unstressed.

yield and seed weight were similar to those of 2 weeks of stress imposed during R2 (R2–3). Yields were reduced by 19%, seed numbers by 33%, and seed weights were increased by 20%. Leaf area index and plant height were reduced in comparison to the unstressed treatment, though not as drastically as on R2–3.

Shaw and Laing (1966) stated that soybeans have rather long periods of flowering and seed-filling, making them more flexible with regard to water stress than is corn. They observed that pod set may be reduced by stress during early flowering but may resume if stress is relieved before flowering ends, and may compensate for some of the reduction that occurred earlier. Thus, reduction in pod set from stress later in the flowering period may reduce seed numbers more than equivalent stress during early flowering. Trends in our data (1983) indicate that our plants followed this pattern. Stress during late flowering (R2–3) reduced seed set more than stress during early flowering (R1–2), and stress throughout flowering (R1–3) reduced seed set more than did either of the shorter stress periods. In 1981 and 1982, stress was imposed at full bloom (R2) and continued to the end of the flowering period, so a compensation in flowering was not observed. Stress-induced reductions in seed set may also be compensated by increased seed weight. Instances of such compensation have been indicated above. Stress imposed during seed filling is more detrimental to yield than that imposed earlier because, with the later stress, there is no compensation for stress-induced pod abortion and reduced seed weight.

Effects of stress during seed filling

Precipitation from early August through September prevented imposition of stress treatments in 1981; thus, data are available only for 1982 and 1983.

Four treatments with stress during seed filling were studied in 1982 and 1983.

Because rain (91 mm, equivalent to an irrigation) on 31 July 1982 made the planned R2–3 treatment similar to R5–6, we modified it by delaying the irrigation at R5 by 7 days and not irrigating after that time (R5–5.5/6.5–7). That treatment produced yields equivalent to the unstressed treatment. Apparently, the 7-day delay changed the distribution of water so that R5–5.5/6.5–7 was not stressed or at least was not stressed as much as R5–6 and R6–7.

The lesser leaf water potentials during seed filling (Table 4) and the greater effects of stress on measured traits show that stress was more drastic in 1983 than in 1982. The more severe stress may have resulted from the higher temperatures and smaller water applications in 1983; however, the larger plant population cannot be discounted as a possible contributor to it.

Stress imposed at R5 and relieved at R6 (R5–6) caused immediate reductions in LAI in both years (Fig. 3 and 4). In 1982, R5–6 yields were reduced by about 15%, whereas in 1983 the reduction was 46% (Table 2). Seed weight was reduced by about 13% and 11% in 1982 and 1983, respectively. Seed numbers were not affected in 1982, but in 1983 they were reduced by 39%. Since the stress was imposed after pods were set and number of seeds per pod was not affected, the reduction in seed number must have resulted from failure of some of the pods to develop after stress was imposed.

Stress throughout the last 5 weeks of the growing period (R5–7) reduced yields by 45% in 1982 and 88% in 1983 (Table 2). Seed weights were reduced by 40% in 1982 and 59% in 1983. While seed numbers were not affected in 1982, they were reduced by 69% in 1983. As in R5–6, the reduction in seed numbers must have resulted from many of the pods failing to develop after stress was imposed. Leaf area index declined rapidly after stress was imposed in both seasons, but the decline was more rapid in 1983 than in 1982.

Stress throughout the last 3 weeks of the growing period (R6–7) reduced yields by 21% in 1982 and 65% in 1983 (Table 2), and seed weights by 24% in 1982 and 46% in 1983. Seed number was not affected in 1982 but was reduced by 36% in 1983. In both seasons, leaf area indexes declined rapidly after stress was imposed. Leaf desiccation and loss occurred earlier in 1983 than in 1982.

In 1982, sufficient stress did not develop in R6.8–7 (stress imposed 6–8 days before physiological maturity) to affect the traits measured; but, in 1983 in R6.5–7 (stress imposed 8–10 days before physiological maturity), seed yield was reduced slightly and seed weight was reduced by 12% (Table 2). Leaf abscission was hastened, as shown in Fig. 4.

Water use efficiency

Seasonal water use efficiencies are given in Table 2. Treatments which were unstressed or only moderately stressed had higher WUEs than those with severe stress. Only in 1982 did the unstressed treatment show a lower WUE than other treatments (R5-5.5/6.5-7, R6.8-7). That occurred because the unstressed treatment received an unnecessary late-season irrigation. Some moderately stressed treatments had WUEs equivalent to those of adequately watered treatments. However, WUEs of stressed treatments did not exceed those of unstressed treatments except in the one case cited above.

There was little depletion of soil water from the 0.90–1.10-m depth, even on the driest treatment. Thus it appears that for soybeans grown in this soil, the effective depth of rooting for water extraction is about 1 m. Mason et al. (1980) found that soybeans used little water from below 1 m in a heavy clay soil, concluding that this water was used only at the expense of considerable yield.

Adaptability for limited irrigation

Drought stress during the early reproductive stages (R1, R2, R3) did not drastically reduce soybean yields, but the crop was more sensitive to stress during bean development and growth (R5-R7; Table 2). In the 3 years, deletion of one irrigation at stages R1, R2, or R3 reduced yields by an average of 10% (3.85–3.45 Mg/ha). In the 2 years for which data are available, deletion of one irrigation at stage R5 or R6 reduced yields by 34% (3.70–2.44 Mg/ha). On the other hand, in 1982, one irrigation was deleted during R5–7 (treatment R5–5.5/6.5–7) without a yield reduction. In 1983, deletion of two irrigations during early reproductive stages reduced yields only 12% (3.13–2.74 Mg/ha), while deletion of two irrigations during stages R5–7 reduced yields by 88% (3.13–0.37 Mg/ha); stress over the same period in 1982 reduced yields by 45% (4.26–2.34 Mg/ha). These reductions are more severe than those reported by Thompson (1977), who measured 30 and 14% yield reductions from terminating irrigation at R5 and R7, respectively. Our results indicate that one or possibly two irrigations may be withheld during late vegetative and early reproductive stages, but no more than one should be withheld during seed development.

Yield reductions from stress during pod filling are very dependent on climatic conditions, and so are highly variable. More research will be necessary to determine whether withholding one irrigation is advisable. Constable and Hearn (1980) found that one or two irrigations could be withheld during the vegetative stage but during pod filling frequent irrigation was necessary to maintain maximum rate of seed growth. Soybeans are amenable to limited irrigation under the stressful climate of the Southern High Plains, but their vulnerability to drought stress during seed development complicates management of limited irrigation. On the basis of published information for corn, cotton, grain sorghum, and wheat, we find that soybeans are more suited for limited irrigation than is corn but are less suited than are cotton, grain sorghum, and wheat.

Musick and Dusek (1980) concluded that because of sensitivity of corn to plant-water stress in the climate of high evaporative demand in the Southern High Plains, limited irrigation of corn should not be practiced. However, cotton, grain sorghum, and wheat are less sensitive to stress and produce economic yields under both limited irrigation and dry farming conditions (Schneider et al., 1969; Stewart et al., 1983).

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